Faculty of Manufacturing Engineering

MICROSTRUCTURAL CHARACTERIZATION AND MECHANICAL PROPERTIES OF Al-Si-Cu ALLOYS PROCESSED BY EQUAL CHANNEL ANGULAR PRESSING

Nurul Naili binti Mohamad Ishak

Master of Science in Manufacturing Engineering

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DECLARATION

I declare that this thesis entitled "Microstructural Characterization and Mechanical Properties of Al- Si- Cu Alloys Processed by Equal Channel Angular Pressing" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature	:	....
Name	:	Nurul Naili binti Mohamad Ishak
Date	:	....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature	:	....
Supervisor Name	:	Dr. Mohd Shukor bin Salleh
Date	:	....

DEDICATION

To my beloved mother, father and family.

ABSTRACT

Recent years, severe plastic deformation (SPD) is recognized as a main technique to produce an ultrafine grained (UFG) structure of aluminium alloys. The most popular and widely applied is equal channel angular pressing (ECAP) technique. Typically, aluminium alloy with dendritic structure is used as feedstock material for ECAP processing. Therefore, in this research a feedstock with a non-dendritic microstructure is preferred to be used in ECAP processing due to the advantage of a good distribution of phase elements in the sample thus increase the mechanical properties of the alloys. The objective of this study is to produce a non-dendritic microstructure feedstock for ECAP process by using cooling slope casting. This study also investigates the evolution of α-Al microstructure, mechanical properties and wear properties of Al-Si-Cu alloys processed by ECAP and to study the effect of T6 heat treatment on α-Al microstructure, mechanical properties and wear properties of Al-Si-Cu alloys. ECAP process were performed by pressing a sample through a 120° die via route A at room temperature. The microstructure of the processed alloys were observed under optical microscope (OM) and scanning electron microscope (SEM) while the mechanical properties of the alloy were validated by Vickers hardness and tensile testing. Sliding wear test was applied to study the wear properties of the alloys. The results obtained indicates that the microstructure features were improves after two ECAP passes as the grain size was obviously refined to 37µm from 75µm in cooling slope cast sample. The hardness and tensile strength of the alloy increased as high as 84.3HV and 237.58MPa after two ECAP passes, compared to the conventional cast alloy with value of 44.6HV and 105.13MPa, respectively. The elongation to fracture decrease from 19% for conventional cast sample, reduce to 12% after processed by ECAP. It was also reveal that the wear resistance of the alloy improved after the combination of cooling slope casting and ECAP process as the volume loss obtained by this sample is lower than other samples with value of 3.3mm^3 under 10N applied load. After T6 treatment, the Si particles was seen to be spheroidised in certain region within the globules within the α-Al globules while the other particles such as Cu, Mg and Fe particles were homogeneously dispersed. After T6, the mechanical and wear properties were enhanced as the distribution of particles were more homogeneous. In T6 condition, sample after 2 ECAP passes shows the highest tensile strength with value of 270MPa and the elongation percentage was also increase to 9% from 5%. Volume loss for alloys after T6 was lower than before T6. After 2 ECAP passes, the volume loss decreased to 3.0mm^3 under 10N load which indicates better wear properties compared to other samples.

ABSTRAK

Kebelakangan ini, ubah bentuk plastik yang teruk (SPD) dikenali sebagai teknik yang utama untuk menghasilkan struktur saiz ira yang sangat halus (UFG). Teknik yang paling popular dan digunakan secara meluas adalah teknik penekanan sudut saluran sama (ECAP). Kebiasaannya, aluminium aloi dengan struktur dendrit digunakan sebagai bahan suapan untuk proses ECAP. Oleh itu, dalam kajian ini, bahan suapan dengan mikrostruktur bukan dendrit dipilih untuk digunakan dalam proses ECAP disebabkan taburan elemen bagi setiap fasa yang terbentuk adalah sekata dan seterusnya dapat meningkatkan sifat mekanik aloi tersebut. Objektif kajian ini adalah untuk menghasilkan aloi yang mempunyai ciri mikrostruktur bukan dendrit sebagai bahan suapan untuk proses ECAP dengan menggunakan teknik tuangan cerun penyejuk. Kajian ini juga dijalankan bagi mengenalpasti evolusi mikrostruktur α-Al, sifat mekanik dan sifat haus aloi Al-Si-Cu selepas proses ECAP dan mengkaji kesan rawatan haba T6 terhadap ciri mikrostruktur α-Al, sifat mekanik dan sifat haus aloi Al-Si-Cu. Proses ECAP dijalankan dengan menekan sampel melalui acuan yang bersudut 120° dengan melalui laluan A pada suhu bilik. Mikrostruktur aloi yang diproses diperhatikan di bawah mikroskop optik (OM) dan mikroskop pengimbasan elektron (SEM) manakala sifat mekanik aloi disahkan dengan menjalani ujian kekerasan Vickers dan ujian tegangan. Ujian haus gelangsar digunakan untuk mengkaji sifat haus aloi. Hasil yang diperoleh menunjukkan bahawa ciri- ciri mikrostruktur bertambah baik selepas laluan kedua ECAP dengan saiz ira yang telah dikurangkan kepada 37µm daripada75µm yang terdapat pada sampel tuangan cerun penyejuk. Nilai kekerasan dan kekuatan tegangan aloi mencapai bacaan setinggi 84.3HV dan 237.58MPa masing-masing selepas laluan kedua ECAP berbanding dengan sampel tuangan konvensional yang hanya peroleh nilai kekerasan sebanyak 44.6HV dan kekuatan tegangan sebanyak 105.13MPa. Pemanjangan sebelum patah berkurang daripada 19% untuk sampel tuangan konvensional, turun kepada 12% selepas proses ECAP. Ini menunjukkan bahawa rintangan haus aloi bertambah baik selepas gabungan antara tuangan cerun penyejuk dan proses ECAP kerana kehilangan isipadu yang diperoleh bagi sampel ini lebih rendah daripada sampel lain dengan nilai 3.3mm^3 dibawah beban 10N. Selepas rawatan haba T6, zarah Si dilihat mengelingini di kawasan lingkungan globula α-Al, manakala zarah- zarah lain seperti Cu, Mg dan Fe tersebar dengan sekata di dalam aloi. Selepas rawatan haba T6, sifat mekanik dan haus juga dapat dipertingkatkan kerana taburan zarah lebih sekata. Dalam kondisi T6, sampel ECAP selepas 2 laluan menunjukkan kekuatan tegangan tertinggi dengan nilai 270MPa dan peratus pemanjangan juga meningkat kepada 9% dari 5%. Kehilangan isipadu aloi selepas T6 adalah lebih rendah daripada sebelum T6. Selepas 2 laluan ECAP, kehilangan isipadu berkurangan kepada 3.0mm^{3}di bawah beban 10N lalu menunjukkan sifat hausnya yang lebih baik daripada sampel yang lain.

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LIST OF ABBREVIATIONS

SPD	-	Severe Plastic Deformation
UFG	-	Ultra fine-grained
ECAP	-	Equal Channel Angular Pressing
CS	-	Cooling slope
OM	-	Optical Microscope
SEM	-	Scanning Electron Microscope
XRD	-	X- ray Diffraction
HV	-	Hardness Vickers
MPa	-	Mega Pascal
SIMA	-	Strain Induced Melt Activated
MIT	-	Massachusetts Institute of Technology
MHD	-	Magneto Hydrodynamic
ITT	-	International Telephone and Telegraph
kHz	-	kilohertz
Al- Si	-	Aluminium- Silicon
Al- Si Cu	-	Aluminium- Silicon- Copper
Al- Ti- B	-	Aluminium- Titanium- Boron
HPT	-	High Pressure Torsion
ABE	-	Accumulative Back Extrusion
ARB	-	Accumulative Roll Bonding
CGP	-	Constrain Groove Pressed
ECAE	-	Equal Channel Angular Extrusion
CP- Ti	-	Commercially pure titanium
TEM	-	Transmission Electron Microscope
HAGBs	-	High angle grain boundaries
LAGBs	-	Low angle grain boundaries
La	-	Lanthanum
Ce	-	Cerium
Sr	-	Strontium
Mg	-	Magnesium
Si	-	Silicon
Fe	-	Iron

Cu	-	Copper
Al	-	Aluminium
SEM- EDX	-	Scanning Electron Microscope- Energy Dispersive X-ray
ASTM	-	American Society for Testing and Materials
SF	-	Shape factor
GS	-	Grain size
COF	-	Coefficient of Friction
φ	-	Channel angle
Ψ	-	Curvature angle
P	-	Pressure
N	-	Number of Passes
V	-	Volume
εN	-	Stain accumulated
µm	-	micrometre
nm	-	nanometre
° C	-	Degree Celsius
°	-	Degree (angle)

LIST OF PUBLICATIONS

Journal

1. Salleh, M. S., Ishak, N. N. M., Yahaya, S. H., Sivaraos and Abdullah, A., 2018. Effect of Equal Channel Angular Pressing on the Microstructure and Mechanical Properties of A356 Alloy. *Journal of Advanced Manufacturing Technology*, 12 (2), pp. 79- 91.

2. Ishak, N. N. M., Salleh, M. S., Yahaya, Mohamad, E., and Sulaiman, M. A., 2017. The Effect of Equal Channel Angular Pressing (ECAP) on the Microstructure and Hardness of A356 Aluminium Alloy. *Journal of Advanced Manufacturing Technology*, 11 (2), pp. 47- 57.

3. Salleh, M. S., Ishak, N. N. M, and Yahaya, S. H., 2017. Microstructural Investigation and Mechanical Properties of Thixoformed Al-6Si-xCu-0.3Mg Alloys. *Jurnal Teknologi*, 79 (5- 2), pp. 27- 31.

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Conference Paper

1. Salleh, M. S., Ishak, N. N. M, and Yahaya, S. H., 2016. Microstructural Investigation and Mechanical Properties of Thixoformed Al-6Si-xCu-0.3Mg Alloys. *5th International Conference on Design and Concurrent Engineering (IDECON 2016)*, Langkawi, Malaysia, 19- 20 September 2016.

CHAPTER 1

INTRODUCTION

This chapter outlines the introduction of this research. In this chapter, the background of the research, objectives of the research, problem statement, scope of study and chapter overview were highlighted.

1.1 Research background

Current lightweight material technologies utilize high-strength steels, non-ferrous metal such as aluminium alloy, magnesium alloy and titanium alloy or secondary heat treatment processes to improve the specific strength of materials. However, production of improved lightweight metals without adding costly alloying elements to present materials or utilizing energy consuming heat treatments are still a major challenge for the production industry. Therefore, to encounter the problem, severe plastic deformation (SPD) technique is introduced as an ultra-fine grained (UFG) materials production. SPD technique refined the grain size down to nanometres size by imposing a high plastic strain to a metal hence generates new grains in the processed samples.

UFG materials are defined as an alloy with average grain sizes less than 1µm and the microstructure are homogeneously distributed with high angle grain boundaries. Generally, average grain size of the alloys plays important role in determining the mechanical properties of the alloys. According to Hall-petch relationship, the yield stress of the metal alloys increase as the grain size decrease. From the relationship, it is verified that UFG materials could enhance the mechanical strength of the alloy. Thus, UFG materials produced by SPD techniques are classified as high strength with large ductility consequently suitable for lightweight applications.

SPD techniques has been implement since 1990s' where many techniques have been proposed and developed. Some major SPD techniques are equal channel angular pressing (ECAP), high pressure torsion (HPT), and accumulative roll bonding (ARB). ECAP is one of popular technique of SPD which involves pressing a billet through a die consisting of two equal channel that intersected at certain angle. In ECAP process, the sample is deformed without any cross-sectional changes of the billet sample. There are four major parameters involved in ECAP process which are processing temperature, channel die angle, number of passes and route. Basically, there are four basic route to define the rotation of the billet between passes. In route A, the billet is pressed without any rotation between passes, route C, the billet are rotated 180° between passes, route B_A where the billet is pressed by rotating at 90° in alternated direction while route B_C, the billet is pressed rotating at 90° in the same direction.

Cast aluminium alloys are commonly used in automation industry due to their good fluidity and mechanical strength. The mechanical properties of cast aluminium alloy somehow is lower compared to the alloys that used other advance processing route such as SPD techniques or semisolid metal processing. Better mechanical properties of that processing are attributed to the globular morphology of α-Al, smaller grain size and homogeneous distribution of intermetallic phase in the sample after the process.

Cooling slope (CS) casting is the advanced semisolid process occupied with simple equipment and low running cost. This method is used by pouring the superheated molten alloy onto the incline plate towards the vertical mould and it is solidified in the mould. This method is a promising techniques that introduced to produce a non-dendritic microstructure feedstock for semisolid metal process, a technology that involves in the formation of metal alloy between solidus and liquidus temperature. In addition, this cooling slope casting method may also suitable to be used in producing a feedstock for SPD technique which is ECAP as it produced a non- dendritic microstructure instead of dendritic that obtained by conventional casting.

Consequently, the aim of this work is to produce a feedstock that have a globular microstructure using a cooling slope casting technique. This study will also investigate the evolution of α-Al microstructure after cooling slope casting in combination with ECAP processing by route A (aluminium sample is press without rotation between passes). The as-cast sample will be machines into a rod shape with diameter of 15mm and then annealed at 540˚C for 8 hours. After that, ECAP experiment will be performed using route A for four passes with channel angle of 120˚. The samples microstructure were then characterized using optical microscope, scanning electron microscope, and X-ray diffraction analysis. The mechanical properties were measured by conducting hardness, tensile and wear testing. Successful outcome from this work should contribute significantly to the improvement of mechanical properties of aluminium alloys.

1.2 Problem statement

In recent years, a studies on ECAP process have been reported in the literature. A review on equal channel angular extrusion as a deformation and grain refinement process had been done by Adedokun in 2011. This article highlighted the review of ECAE process including the advantages and limitations, the parameters and also the material tested. In 2013, Estrin and Vinogradov wrote on the challenging parts of SPD and some highlights to the potentials and limitations of SPD technologies. Roodposhti et al. (2015) studied the effect of ECAP process parameters including pressing route, temperature, pressing speed, channel and curvature angle and number of passes through the die to the commercially pure titanium (CP-Ti) alloys. There are many literatures have been reported on utilizing ECAP on titanium alloy and magnesium alloy, but there are limited study on aluminium alloy. Therefore, aluminium alloy is choose to undergo ECAP process in this research.

Cast aluminium alloys are frequently used in automotive and aeronautical industry. The low production cost of conventional casting processing routes comes with several drawbacks, such as the formation of porosity, hot tears and segregation which may act as a potential crack source during service. Futhermore, in the conventional processes, like forging, some defects initiate reducing the mechanical properties of the aluminium alloys. Some of aluminium cast alloys are not suitable to be used in a critical application such as in engine block because of some limitation such as low mechanical properties and high porosity. This will detrimental the possibility of the particular alloys to be used in automotive industry. Therefore, there have been considerable efforts to minimize these problems which resulted in introducing advanced shaping routes such as ECAP. UFG alloys produced by ECAP have superior mechanical properties resulting from significant grain refinement together with dislocation strengthening. This technique produce better mechanical properties of aluminium alloys compared to the conventional cast alloys. Normally in ECAP, a feedstock with a dendritic α-Al microstructure is being used. Dendritic structure tend to produce a porosity which detrimental the mechanical properties if the samples. Therefore, cooling slope casting technique is applied in order to obtain near globular microstructure instead of dendrite microstructure to be used in ECAP process.

1.3 Research objectives

The objectives of this research involve:

1. To produce a non-dendritic microstructure of Al- Si- Cu alloy feedstock for ECAP process by using the cooling slope method.
2. To investigate the evolution of α- Al microstructure, mechanical and wear properties of Al- Si Cu alloy after equal channel angular pressing (ECAP) process.
3. To investigate the effect of T6 heat treatment on microstructure evolution, mechanical and wear properties of Al- Si- Cu alloy.

1.4 Research scope

This research begin with the production of the feedstock for ECAP process by using cooling slope casting technique and conventional casting. Cooling slope casting technique was applied in order to obtain non- dendritic feedstock as fulfil the first objective. Cooling slope casting is done at different pouring temperature of 625°C, 635°C and 645°C and different slope length which are 200mm, 300mm and 400mm. ECAP process is performed by using a die with channel angle of 120° for two passes via route A at room temperature. The aim of this research to investigate the evolution of α-Al microstructure after cooling slope casting in combination with ECAP processing were done with an aid of optical microscope (OM), scanning electron microscope (SEM), and x-ray diffraction analysis (XRD). The research also involves on investigating the mechanical properties of aluminium alloy after ECAP processing by undergo tensile testing and hardness testing. Whereas a wear test is done by subjected the materials to sliding wear test.